Recent advances in the study of Micro/Nano Robotics in France.

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Abstract— **In France, during the last decade, significant research activities have been performed in the field of micro and nano robotics. Generally speaking the microrobotic field deals with the design, the fabrication and the control of microrobots and microrobotic cells. These microrobots are intended to perform various tasks in the so-called Microworld. The scale effects from macroworld to microworld deeply affect robots in the sense that new hard constraints appear as well as new manufacturing facilities. Concerning the nanorobotics, in order to achieve high-efficiency and three-dimensional nanomanipulation and nanoassembly, parallel imaging/manipulation force microscopy and three-dimensional manipulation force microscope, as well as nanmanipulation in the scanning electron microscope, have been developed. Manipulation of nanocomponents, such as nanoparticles, nanowires and nanotubes, have been addressed to build two-dimensional nano patterns and three-dimensional nano structure.**

I. Introduction

In France, micro/nanorobticis research are mainly addressed at two institutes: (i) Automated Systems for Micromanipulation and Microassembly (SAMMI) group of AS2M Department of FEMTO-ST in Besançon, France. (ii) Institut des Systèmes Intelligents et Robotique (ISIR), Université Pierre et Marie Curie-Paris VI/CNRS, 4 Place Jussieu, 75005 Paris, France.

At FEMTO-ST, significant activities have been performed in micro/nanorobotics:

1) Design, fabrication and the control of microrobots and microrobotic cells.
2) Research on micro scale effects.
3) Micro force sensing and control.
4) Techniques on micro/nano positioning.
5) Design and fabrication micro-grippers.

At ISIR, research activities on micro/nanorobotics are mainly focused on:

1) Design, fabrication and the control of microrobots.
2) Develop haptic devices for macro-micro/nano coupling.
3) Micro/nano physics phenomena.
4) High-efficiency and three-dimensional AFM-based nanomanipulation and nanoassembly.
5) Nanomanipulation and nanoassembly in scanning electron microscope.

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This paper is organized as follows: research on microrobots at FEMTO-ST and ISIR will be introduced in section II. In section III, nanomanipulation and nanoassembly at ISIR will be discussed and section IV concluded the paper.

II. Microrobots Research at FEMTO-ST and ISIR

A. Micromanipulation and Microasembly at FEMTO-ST

In this framework, most of the research of the SAMMI (Automated Systems for Micromanipulation and Microassembly) group of AS2M Department of FEMTO-ST in Besançon, France, deals with the micromanipulation and micro assembly issues. More precisely, FEMTO-ST deals with robotic motions, perception, control and manipulation at the microscale and also new activities at the nanoscale.

It corresponds to various and multidisciplinary scientific issues:

1) Microrobotic and adaptronic systems: systems for feeding, carrying, gripping, micrometer size and microfabricated robotics, strategies for microassembly.
2) Advanced control of dynamic and complex systems: modelling and control of microactuators microsystems, and smart materials, of discrete or continuous distributed systems, control by exteroceptive sensors notably by vision.
3) Micromanipulation and microassembly: characterization of the interactions in the microworld, strategies for microhandling based on physical principles relevant at this scale.
4) Perception and measurement: measure of microforces and artificial vision.

An overview of the femto-st activities in micro and nanorobotics is given below, included the main references.

1) Modelling and Simulation: The characterisation (modelling or measurement) of the specific forces of microscale is necessary to design robotic systems for micromanipulation. The study of micromanipulation strategies is usually limited by two major problems: (i) the lack of microforce models usable by the robotic community, (ii) the shortage of force sensors really suitable to measure these effects. Current works in FEMTO-ST and ISIR institutes deal with the development of scientific platforms to address these issues. We are focusing on: (i) simulation of the behavior of micro-objects to improve the design of new microrobotic methods and, (ii) the measure of the forces to validate the simulations (see in figure 1). These works enables to increase the knowledge of the microworld phenomena necessary to the development of microrobotic scientific activities [1–4, 21].

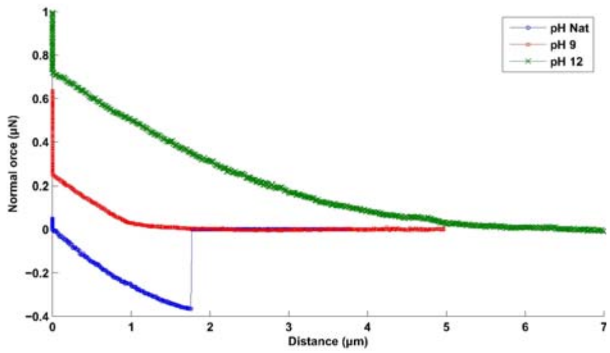

Fig. 1. Examples of a distance-force curves measured with an AFM in order to characterized the interaction forces between micrigrippers and micro-objects : This curves show the impact of the Ph of a solution on the interaction between functionnalised surfaces, the behaviour is attractive at natural pH and repulsive in case of basic solution [23,24].

2) Robotic Microhandling Methods: The development of new robotic microhandling methods is a key point to fabricate hybrid micro-systems as well as micromechatronic products. At present, the release task is the most critical and unreliable phase because of the impact of the surface forces and adhesion forces. Theoretical and experimental comparative analysis between the water medium and the air show that both types of medium show the potential interest of the liquid in micromanipulation applications [3, 4]. In fact, surface and adhesion forces decrease significantly in water while the hydrodynamic force increases. Both phenomena are able to reduce respectively the electrostatic and adhesion perturbations and the loss of micro-objects. Manipulation of artificial objects in water is consequently a promise to obtain reliable handling. Some submerged microhandling strategies have been studied in FEMTO-ST (see in figure 2). Negative dielectrophoresis can be used to control the release of an object grasped with a two-fingered gripper [22]. Submerged freeze gripping enables the grasping with high blocking force and the release of micro-objects without adhesion perturbations [25]. At least, chemical properties of the medium (e.g. pH) can be used to directly control the surface behavior of functionalized objects and gripper. This chemical control is able to switch interactions between gripper and object from attraction to repulsion [23, 24].

3) Microrobotic and Adaptronic Systems: About microrobotic systems, we design and realize microrobots based on the used of actuators adapted to the small size. Notably, we propose modelling and control of smart materials like piezoelectric materials, shape memory alloys and magnetic

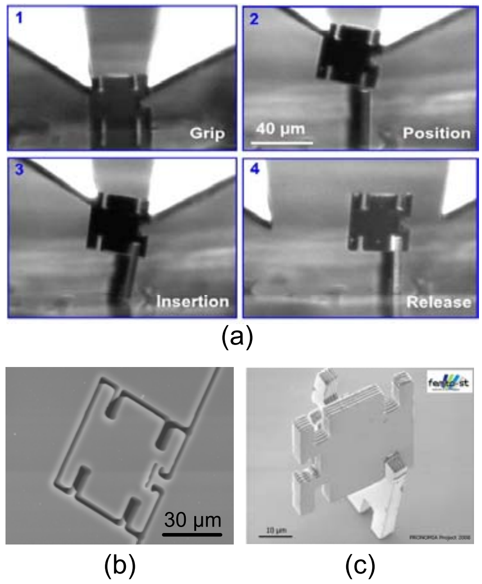

Fig. 3. Assembly of an optical microbenches at FEMTO-ST. (a) Microassembly system configuration. (b) Micromachined rail. (c) Manipulation result.

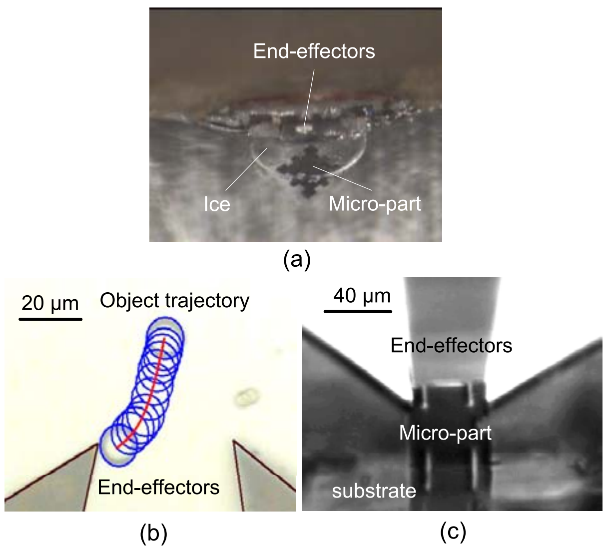

Fig. 2. Microhandling strategies. (a) Handling by submerged ice [25]. (b) Dielectrophresesis release [22]. (c) Manipulation with tweezer [29]

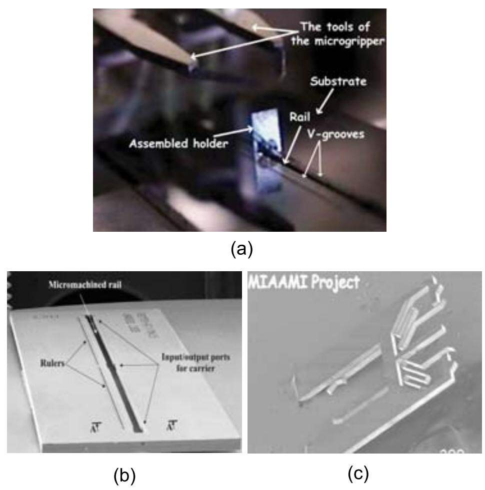

Fig. 4. Example of a microassembly done with a robotic platform of FEMTO-ST. (a) Micro-object on the substrate. (b) Assembly of 2 microojects. (c) Assembled microobjects.

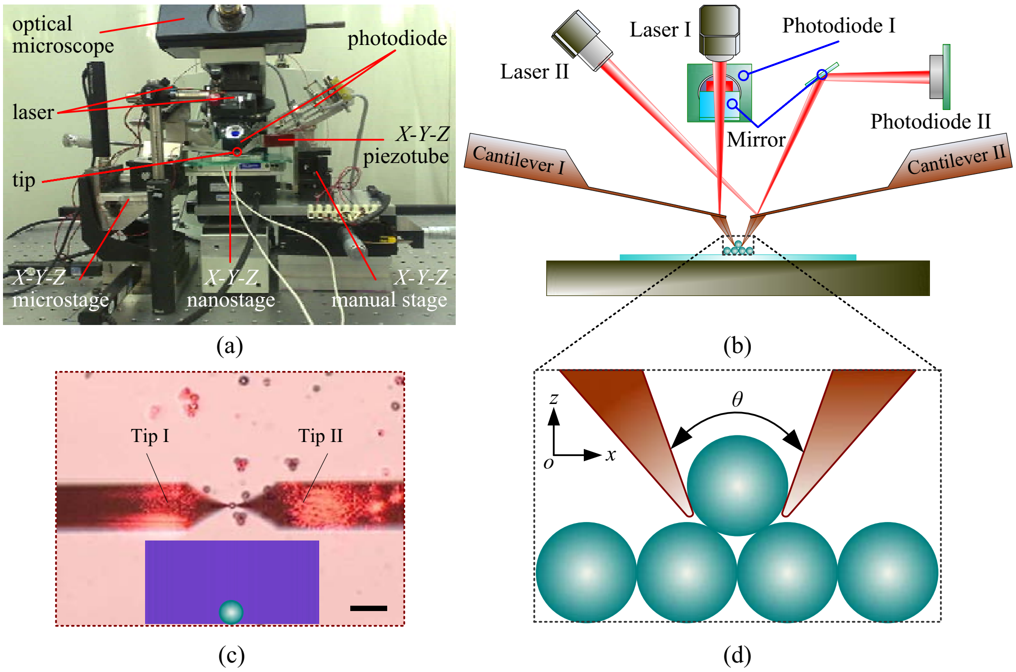

Fig. 5. (a) A photo of the 3DMS. (b) System configuration of the 3DMS. (c) A microscopic image captured during the pickup operation of a microsphere using the nanotip gripper. The bottom insert shows the pick-and-place manipulation scheme with a nanotip gripper. The scale bar represents 20 μm. (d) A zoomed figure shows the scheme of grasping operation with a nanotip gripper [31].

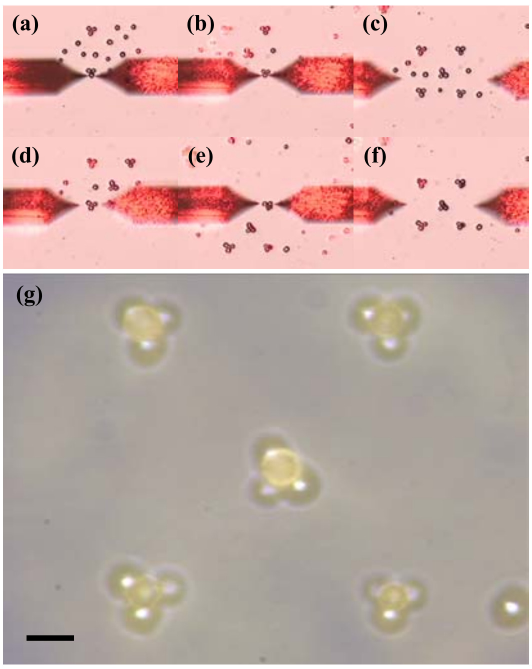

Fig. 6. Assembly results. (a)C(c) show three images intercepted from assembly process of the first layer of the micropyramids. (d)C(f) depict assembly process of the second layer of the micropyramids. The images (a)C(f) are captured under magnification of 20 μm. (g) The 3D microassembly results under magnification of 100×, in which the scale bar represents 5 μm [31].

shape memory alloys [5-9, 16, 17]. The smart actuators are redesigned to integrate new microrobotics structures that give interesting repeatability, precision and dynamics. These structures can be included in air or liquid media [10-15]. The control of MEMS and particularly of nanotwezeers is also a research activity in femto-st. The aim is to develop control techniques that enable to reach very high precision, under the nanometer when comb drive actuators are used or piezo actuators. A last explored domain is the proposal of advanced control for smart surfaces.

In order to test our original strategies, some microassembly platforms have been built and integrated several elementary works presented above. We focus our works on the study of the packaging and the assembly of silicon microparts in order to produce microscopic assembly systems [27, 28]. An original hybrid method between adhesion manipulation and standard gripping has been proposed [29]. A complete teleoperated robotic structure included micropositioning stages, vision capabilities, piezogripper with silicon end-effectors, has been built. Our micro-assembly demonstrators are able to perform (i) teleoperated assembly of micro-objects in 30 seconds; (ii) automatic pick-and-places along two degrees of freedom in an open loop with a time cycle of 1.8 seconds; (iii) automatic pick-and-places along four degrees of freedom using visual servoing in 90 seconds (see in figure 2) Note that an application field for microassembly is the realization of microoptical benches. We have designed holders and supports with rails to obtain reconfigurable and adjustable benches (see in figure 3). In the point of view of the control, we have proposed hybrid force/position control to guide optical holders in the rails.

B. Micromanipulation and Microasembly at ISIR

Three-dimensional (3-D) automated micromanipulation at the scale of several micrometers using three-dimensional micromanipulation system (3DMS) with a nanotip gripper has been developed at ISIR [31]. The gripper is constructed from protrudent tips of two individually actuated atomic force microscope cantilevers (seen in Fig. 5); each cantilever is equipped with an optical lever. A manipulation protocol allows these two cantilevers to form a gripper to pick-and-place microobjects without adhesive-force obstacles in air. For grasping, amplitude feedback from the dithering cantilever with its normal resonant frequency is used to search a grasping point by laterally scanning the side of the microspheres. Real-time force sensing is available for monitoring the whole pick-and-place process with pickup, transport and release steps. For trajectory planning, an algorithm based on the shortest path solution is used to obtained 3-D micropatterns with high levels of efficiency. In experiments, twenty microspheres with diameters from 3 μm to 4 μm were manipulated and five 3-D micropyramids with two layers were built (seen in Fig. 6). 3-D micromanipulation and microassembly at the scale of several microns to the submicron scale could become feasible through the newly developed 3-D micromanipulation system with a nanotip gripper.

III. Nanorobotics Research at ISIR

A. Two-Tip Atomic Force Microscope

The Two-Tip Atomic Force Microscope is equipped with an optical microscope (Olympus BX50WI) and two sets of devices commonly used in a conventional AFM, mainly including two cantilevers with two sets of nanopositioning devices and optical levers. As shown in Fig. 1 (a), one *XYZ* piezoelectric actuated nanostage (MCL Nano–Bio2M) with a maximum scan range of 50 μm $\times$ 50 μm $\times$ 50 μm and a *XYZ* piezotube (PI P–153.10H) with a scan range of 10 μm $\times$ 10 μm $\times$ 10 μm are used. Note that hysteresis of the piezotube are well compensated by PI operator [32]. The AFM cantilevers with protrudent tips (ATEC–FM), as shown in right inset of Fig. 1 (a), are employed as end-effectors for image scanning and manipulation. Two sets of optical levers, typically composed of a laser and a quadrant photodiode, are arranged on two vertical planes and used to detect actions of cantilevers during the manipulation, as shown in Fig. 1. This system can be used for high-efficiency parallel nanomanipulation and three-dimensional nanomanipulation.

B. Parallel Manipulation Force Microscopy

The atomic force microscope (AFM) has been widely used to manipulate nanoparticles, nanowires and nanotubes for applications, such as, nano-structure building, nano-characterization and bio-manipulation. However, conventional AFM-based nanomanipulation is inefficient because of the serial scan-manipulation-scan process involved. In this paper, high-efficiency automated nanomanipulation with the

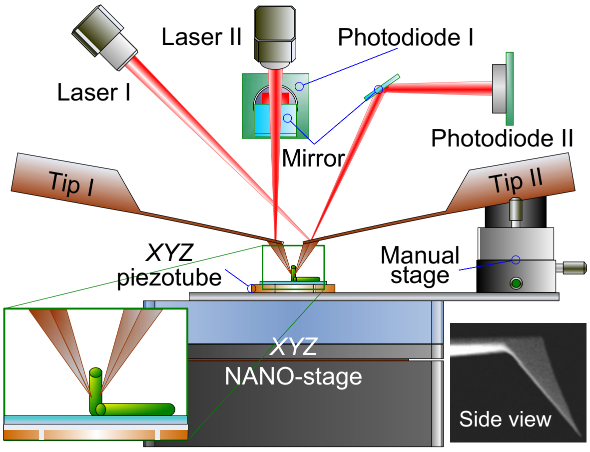

Fig. 7. System configuration of the Two-Tip Atomic Force Microscope [33].

developed parallel imaging/manipulation force microscope (PIMM) is presented. With the PIMM, image scan and nanomanipulation can be performed in parallel through the collaboration between two cantilevers: one cantilever acts as an imaging sensor and the other is used as a manipulating tool. Two automated manipulation schemes were introduced for normal- and high-speed image scanning, respectively. An automated parallel manipulation task is managed by system control software with multi-thread through a procedure of dynamic image processing, task planning, two-tip collaboration, and a controlled nanoparticle pushing with the force or amplitude feedback from both the cantilevers. The efficiency of automated parallel nanomanipulation with normal-speed image scanning was validated by building nanoparticle patterns [33].

A parallel manipulation results is shown in Fig. 8. High-speed image scan is not yet available on the current system.

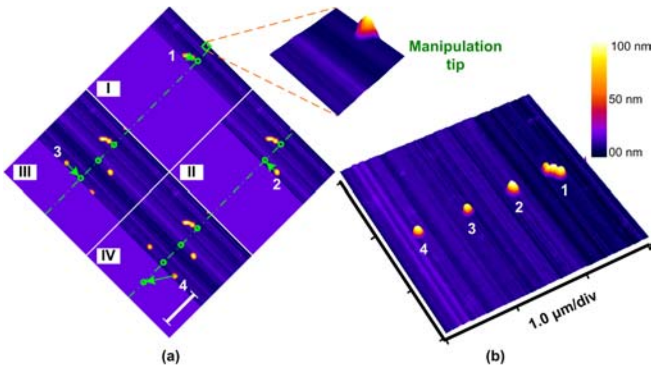

Fig. 8. A parallel imaging/manipulation result with a normal-speed image scan of tip I. (a) Emergences of four particles (with a diameter of 74nm - 82nm) on four different dynamic displays, namely, image I to IV. Once one particle has been fully scanned, a corresponding manipulation task will be activated to push it to its destination. (b) A manipulation result. Four nanoparticles were pushed along a line within the frame period of the image scan. The total manipulation time for these four particles was less than one minute, which is much less than the entire imaging time of ten minutes [33].

However, a parallel image/manipulation task was performed with a normal-speed image scan on the PIMM we developed. Manipulation results are shown in Fig. 3, in which four Ag nanoparticles with a diameter of 74 nm-82 nm, emerged on dynamic image I to IV in sequence, were pushed onto the image midline during the image scan. In the experiment, the frame period was about ten minutes. In contrast, the total manipulation time of these four nanoparticles was less than one minute with a pushing velocity of about 300 nm/s. These results indicate that we can complete a more complex manipulation task during the image scanning thread to greatly increase the efficiency of the AFM-based nanomanipulation and making mass production feasible.

C. 3-D Nanomanipulation and Nanoassembly

Applications of the conventional atomic force microscope (AFM) succeeded in manipulating nanoparticles, nanowires or nanotubes by widely used pushing or pulling operations on a single plane. However, pick-and-place nanomanipulation is still a challenge in the air. In this paper, a modified two-tip AFM (seen in Fig. 7), called three-dimensional (3D) manipulation force microscope (3DMFM) was developed, aiming to achieve the pick-and-place in the air. This system mainly consists of two microcantilevers and each is quipped with a nanopositioning device and an optical lever, constructing a nanotweezer with capabilities of picking and releasing nanoobjects with force sensing. Before the 3D manipulation, one of the cantilevers is employed to position nanoobjects and locate the tip of another cantilever by image scanning, then these two cantilevers fit together as a nanotweezer to grasp, transport and place the nanoobjects with real-time force sensing. In pick-and-place experiments, silicon nanowires (SiNMs) with different diameters were manipulated and 3D nanowire crosses were achieved [34]. 3D nanomanipulation and nanoassembly in the air could become feasible through the newly developed 3DMFM.

Figures 9 exhibits the 3D manipulation of the SiNWs with a diameter of 25 nm (top) $\sim$ 200 nm (root). A scanned image 9 μm $\times$ 9 μm is shown in Fig. 9 (a), which includes the topographic image of several nanowires, and of course also involves the local image of Tip II (see the insert). A Grasping location of the nanowire are marked with a short green line A–A, where the nanowire has a height of 166 nm, as seen in the top insert. Fig. 9(c) shows the re-scanning image after pick-and-place manipulation. It can be found that the nanowire has been successfully transported and placed onto another nanowire to build a nanocross. A full force curve was recorded from the force response on Tip II, as shown in Fig. 9 (b). The force curve exhibits four steps, including grasping, picking up, transporting and placing.

Another type of cone-shaped SiNWs with diameters of 15 nm (top)$\sim$ 70 nm (root) were manipulated as seen in Fig. 10. After image scan shown in Fig. 10 (a), three silicon nanowires were selected and the manipulation locations were placed near the top, the root and on the middle part of the SiNWs, marked by short green lines B–B, C–C and D–D, respectively. The SiNWs heights on these locations are 46 nm, 66nm and 58 nm, respectively. In the first grasping on the location B–B, after successful contact detection on Tip II, as Tip I approach the nanowire to form a nanotweezer, the "dig into" response did not occur, that meant the first silicon nanowire could not be picked up but be pushed by Tip I, which is verified on the Fig. 10 (b). On the second manipulation location C–C, the 3DMFM succeeded in pick-and-place manipulation and building a nanocross.

IV. Conclusion

Researches on micro/nanorobotics at two institutes FEMTO-ST and ISIR, as French representatives in the field of micro/nanorobotics, have been introduced. In the field of microrobotics, concerning system design and building, manipulation principle and strategies, force sensing and control, and manipulation results, research activities at both institutes have been presented. For nanomanipulation, present work at ISIR, including parallel nanomanipulation and three-dimensional nanomanipualtion and nanoassembly, have been briefly presented.

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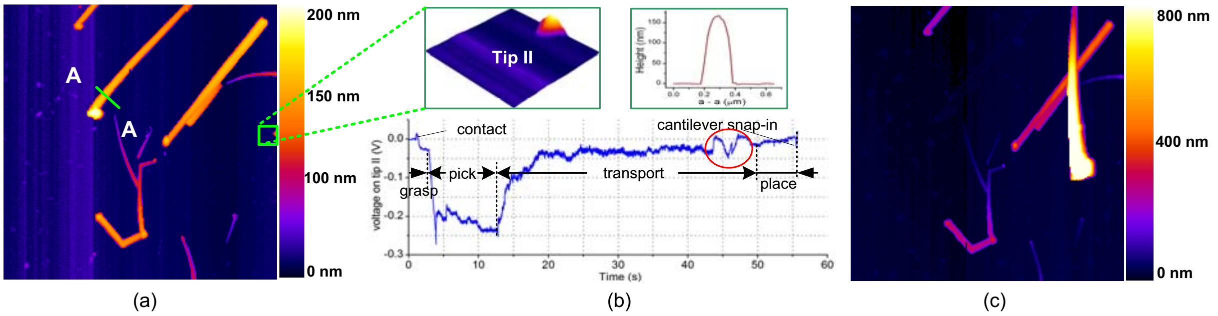

Fig. 9. Building a nanocross using SiNWs with diameters of 25 nm (top) $\sim$ 200nm (root). (a) A pre-scanned image. (b) A full force curve on Tip II. Inserts show the zoom topography of Tip II and height information at A–A. (c) A post-manipulation image shows that a nanocross has been built [34].

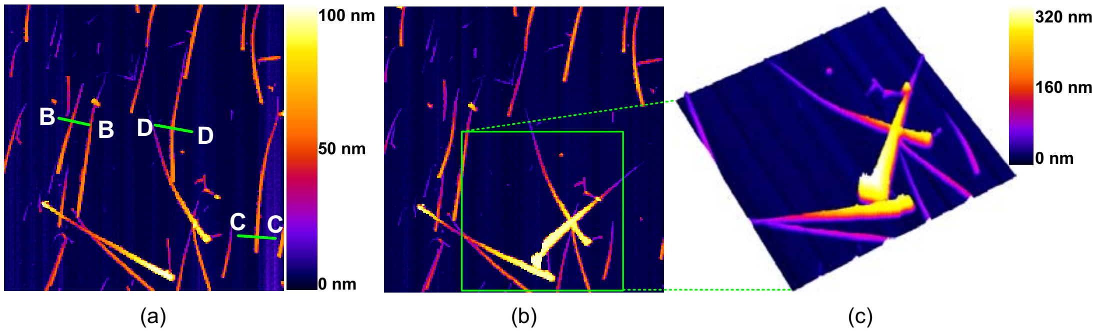

Fig. 10. Building a nanocross using SiNWs with diameters of 15 nm (top) $\sim$ 70nm (root). (a)A pre-scanned image. (b)A post-manipulation image shows manipulation results. (c) A zoom topography of the nanocrossbar [34].

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